Precise Point Positioning in a New GNSS Era

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Abstract

The rapid changes in the Global Navigation Satellite Systems (GNSS), with the modernization of GPS and GLONASS and the emergence of BeiDou and Galileo, will play a key role for the reliability and accuracy of high-precision GNSS applications. The redundant observables and the additional frequencies can vastly enhance the geodetic positioning techniques and thus provide significantly improved solutions even in challenging environments, where the visibility of GPS-only satellites is degraded. This paper presents an investigation and analysis of accuracy improvement techniques in the so-called Precise Point Positioning (PPP) method using signals from the fully operational (GPS and GLONASS), as well as the emerging (Galileo and BeiDou) GNSS systems. The main aim was to determine the improvement in both the positioning accuracy achieved and the time convergence it takes to achieve geodetic-level (10 cm or less) accuracy. To this end, freely available observation data and precise orbit and clock products from the recent Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS), as well as the open source program RTKLIB were used.

Keywords: Precise Point Positioning, Multi-GNSS, MGEX, RTKLIB

Introduction

Since the 1990s, the Global Positioning System (GPS) has been an integral part of modern technological infrastructure and services. Each GPS satellite broadcasts modulated signals with Position, Navigation and Timing (PNT) information so as to enable user-receivers on the Earth’s surface to determine position, velocity and time that are essential for a wide range of daily life applications.

Traditionally, for the determination of a user’s position, differential positioning were used almost extensively, since most of the errors in the observations of closely- and/or widely-spaced stations are largely eliminated. There are, however, two major drawbacks of the method: there is a need to have at least one reference station in the vicinity of a user and, to acquire simultaneous observations both in

the reference and unknown sites. More recently, a solution to this problem was introduced with a new positioning method, the so-called Precise Point Positioning (PPP) (Zumberge et al., 1997), which exploits both the carrier phase and code observations by using only a single receiver and the precise orbit and clock products distributed by the International GNSS Service (IGS). As it is expected, the PPP method leads to a significant decrease of both the cost and equipment required in the field. This is the reason this method is being used nowadays in a variety of applications like remote sensing, natural hazard monitoring, robotics, precision farming and airborne mapping. However, PPP performance is heavily affected by a factor called convergence time, which is the time required for the PPP solutions to achieve geodetic-level positioning accuracy.

Typically, the positioning accuracy of PPP solutions can be better than 10 cm after a convergence time of about 20-30 minutes using solely GPS observational data. A way of improving this technique, which nowadays attracts great interest from the geodetic community, is the fusion of observational data from all the available today GNSS systems, including the Russian GLONASS, the European Galileo and the Chinese BeiDou. This is mainly due to a significant increase in the number of observed satellites and the optimization of satellite geometry, which in turn improve continuity and reliability of positioning (Li et al., 2015a). This improvement technique has been the main subject of this study focusing on a detailed investigation of the positioning accuracy and convergence time improvement of PPP solutions using multiple GNSS data.

1. PPP Mathematical Model

The GNSS observation equations for measuring a pseudorange P and a carrier phase L in the i-th signal frequency can be described by the following general expressions (in units of length):

$$P_i^s = \rho^s + c\,dt^s - c\,dT^s + d_{orb}^s + d_{trop}^s + d_{ion,P_i}^s + \varepsilon_{P_i}^s \tag{1}$$

$$L_i^s = \rho^s + c\,dt^s - c\,dT^s + d_{orb}^s + d_{trop}^s - d_{ion,L_i}^s + dL_i^s + \lambda_i^s\,\mathrm{N}_i^s + \varepsilon_i^s \tag{2}$$

where the indices *s* and *i* refer to the GNSS satellites and the signal frequency being used; P_i and L_i are the measured pseudorange and carrier phase range; ρ is the true geometric distance between the satellite and receiver antenna phase centers; *c* is the speed of light in vacuum; *dt* and *dT* are the receiver and satellite clock biases; d_{orb} is the satellite orbit error; d_{trop} is the tropospheric error; $d_{ion,Pi}$ and $d_{ion,Li}$ are the ionospheric errors for the pseudorange and phase observations

respectively; λ is the signal's wavelength; N is the ambiguity term; dL_i is the combined phase correction term for the phase center offsets and variations, the site displacements and the phase windup effect; ε_{Pi} and ε_{Li} are the measurement errors for the pseudorange and carrier phase observations.

In practice, prior to using the previous equations, the observations have to be corrected for the satellite orbit and clock errors by using the precise orbit and clock products provided by International GNSS Service (IGS). In addition, the traditional PPP algorithm is based on the linear combination of the carrier phase and code observations in two frequencies so as to eliminate the first order ionospheric error. As a result, the following ionosphere-free equations are used for the position determination:

$$P_{IF}^{s} = \frac{f_1^2}{f_1^2 - f_2^2} P_1^s - \frac{f_2^2}{f_1^2 - f_2^2} P_2^s = \rho^s + c\,dt^s + d_{trop}^s + \varepsilon_{P_{IF}}^s \tag{3}$$

$$L_{IF}^{s} = \frac{f_1^2}{f_1^2 - f_2^2} L_1^s - \frac{f_2^2}{f_1^2 - f_2^2} L_2^s = \rho^s + c\,dt^s + d_{trop}^s + dL_{i,IF}^s + N_{IF}^s + \varepsilon_{P_{IF}}^s \tag{4}$$

Therefore, the PPP model of equations (3) and (4) can be used for any GNSS system observable. When dealing with a fusion of observables from different GNSS systems, one could consider adding an inter-system bias (ISB) in the previous mathematical model. In this study however, we have not considered this option based on the study of Chen et al. (2015) which showed that the correlation coefficient of ISB and the station's position estimates is nearly zero.

2. Multi-GNSS Experiment

Although IGS, since 2011, has undertaken the mission for collecting, archiving and distributing observational data and products from a global station network for the full operational GPS and GLONASS constellations, the GNSS changes which have occurred with the deployment of the European and Chinese satellite navigation systems have led to the creation of the Multi-GNSS Experiment (MGEX) pilot project. The objective of MGEX is the collection and analysis of observations and distribution of precise products from all the available GNSS systems: i.e., GPS and GLONASS, as well as the upcoming Galileo, BeiDou, QZSS, and IRNSS.

The current status of the Global Navigation Satellite Systems is given in Table 1. Satellites marked in brackets are the operational satellites at the time of this study,

while those marked with an asterisk are not yet operational. The Indian satellite system, formerly known as IRNSS, has been renamed to NAVIC as of April 2016.

Currently, the MGEX multi-GNSS monitoring network consists of some 140 stations running in parallel to the legacy IGS network. These provide an almost global coverage, with each station supporting signals from at least one of the new GNSS systems. The orbit and clock products for the new constellations which are required for high-precision GNSS applications are generated on a routine basis by five MGEX analysis centers (CNES/CLS, CODE, GFZ, TUM, Wuhan Univ.) and are available at the CDDIS MGEX product depository and the mirror sites hosted by IGN and ENSG.

Table 1: Current status of global and regional navigation satellite systems as of May 2016.

System	**Blocks**	**Signals**	**Operational satellites**
GPS	IIA	L1 C/A, L1/L2, P(Y)	0, [3]
	IIR–A/B	L1 C/A, L1/L2, P(Y)	12, [12]
	IIR–M	+L2C	7, [7]
	IIF	+L5	12, [9]
GLONASS	M	L1/L2 C/A + P	23, [24]
	K	L3	1, [2]
BeiDou	GEO	B1, B2, B3	5, [5]
	IGSO	B1, B2, B3	5, [5]
	MEO	B1, B2, B3	5, [4]
Galileo	IOV	E1, (E6), E5a, E5b, E5ab	3, [3]
	FOC	E1, (E6), E5a, E5b, E5ab	6, [4]
QZSS	n/a	L1 C/A, L1C, L2C, E6 LEX, L5	1, [1]
NAVIC (IRNSS)	n/a	L5, S	7*, [4*]

The build-up of the MGEX network has helped in the early familiarization with new GNSS signals and systems (Montenbruck et al., 2014) and its future continuous operation will provide new capabilities for enhanced and robust positioning models since the fusion of multiple GNSS data will vastly increase the number of observed satellites as well as improve their geometry, and thus lead to more reliable positioning results. Relevant studies (Cai and Gao, 2013; Yigit et al., 2014; Cai et al., 2015; Li et al., 2015a; Li et al., 2015b) have already indicated that PPP solutions based on observational data from more than one GNSS constellations lead to great improvements both in the positioning accuracy and the time convergence it takes for the solutions to achieve satisfactory accuracy levels.

3. Data Acquisition, Processing and Analysis

For the present study, GNSS observational data from 10 days in 2014 were obtained for the MGEX stations UNB3 and CUT0, whereas the precise orbit and clock products required for their analyses were retrieved from CODE Analysis Centre.

In order to assess both the positioning accuracy and the time convergence it takes to achieve geodetic-level accuracy using multiple GNSS systems, the analyses of the available data from the two MGEX stations were carried out in both single- and multi-GNSS modes. The processing engine used in this study is the open-source software suite RTKLIB, which provides its users with the capability of processing multi-constellation data. Linear combinations of the available pseudorange and carrier phase observations in two frequencies per GNSS system were used so as to eliminate the first order ionospheric error and get estimates for the integer ambiguities and the tropospheric delays. Table 2 summarizes the processing strategy and models that were considered in the study.

The computed station coordinates were compared with those obtained from a 10-day combination solution using GPS, GLONASS, Galileo and BeiDou data, whereby the spatial geometry and the position accuracy that is achieved can be considered that is theoretically optimized due to the significant increase in the number of observed satellites.

A measure of position accuracy of PPP solutions for various scenarios (with regard to session duration, the elevation cut-off angle and the integer ambiguity resolution capability) was obtained with respect to the 10-day solution using the Root Mean Square Deviation (RMSD) indicator:

$$RMSD = \sqrt{(1/n)\sum_{t}^{n}(x_{1,t} - x_{2,t})} \qquad (5)$$

where the $x_{1,t}$ and $x_{2,t}$ refer to the 10-day solution time series and specific scenario solution respectively, and n is the total number of observations.

Table 2: Processing strategy and error modeling for the multi-GNSS observational data used in the program RTKLIB

Frequencies	L1/L2 (GPS/GLONASS), L1/L5 (Galileo), B1/B2 (BeiDou)
Observations / Sampling rate	Carrier phase and pseudorange / 30 s
Elevation cutoff angle	10° (20°, 30°, 40°)
Satellite orbits and clocks	Fixed (comwwwwd.sp3 and comwwwwd.clk files)
Ionospheric delay	Linear combination of carrier phase and pseudorange observations in 2 frequencies
Tropospheric delay	Estimated as unknown with NMF
Satellite antenna phase center	Corrected (igs08.atx)
Receiver antenna phase center	Corrected (igs08.atx)
Site displacements	Solid Earth tides, Pole tides, Ocean tide loading according to IERS Convention 1996 (2010)
Phase windup effect	Corrected
Differential code biases	Corrected for P1-C1 (P1C1yymm_RINEX.DCB)
Earth rotation parameters	Fixed (comwwwwd.erp)
Station coordinates	Estimated in both static and kinematic modes
Reference frame	ITRF
Receiver clock	Estimated w.r.t. the time scale of every GNSS
Phase ambiguities	Estimated as real values (integer values only by using CNES products)

4. Results

In this section, the results with regard to session duration, elevation cut-off angle and integer ambiguity resolution investigation are presented.

4.1 Session duration

The first analysis scenario aimed at investigating how the session duration affects the PPP position estimates in single- and multi-GNSS modes.

As shown in Figure 1, typically the positioning accuracy for GPS- and GLONASS-only solutions can be better than 10 cm after a convergence time of about 30 and 40 minutes respectively. A significant improvement is noted in the combined GPS/GLONASS solutions, whereas the improvement is less noticeable in the case of GPS/Galileo and GPS/BeiDou solutions, mainly due to the small number of currently available Galileo satellites and the low visibility of the BeiDou satellites at station UNB3. The corresponding combined solution from four GNSS systems shows a much faster convergence to the level of 10 cm and the highest accuracy for all three coordinate components. This is illustrated by the fact that it takes only 2, 1 and 5 minutes for the multi-GNSS solution to achieve this accuracy compared to the GPS-only solution which converges in 5, 4 and 30 minutes respectively in the North, East and Up directions. In all other tests the improvement was about 15-25%, 10-30%, 20-25% in the positioning accuracy achieved in the same directions by multi-GNSS solutions compared to GPS-only solutions respectively.

Figure 2 shows the statistical results generated after the processing of all selected days' data with different session duration at station CUT0. It is clearly illustrated that longer sessions result in a decrease of the RMSD values, and subsequently to an evident improvement of the PPP positioning accuracy, as it is also showed by Li et al. (2015a). It is also worth pointing out that the GPS-only PPP solutions achieve higher accuracy than GLONASS-only PPP solutions, while both single-GNSS PPP solutions have in general worse performance in comparison with the multi-GNSS modes. In particular, GPS/GLONASS and GPS/GLONASS/Galileo/BeiDou PPP solutions show significant improvement even in small observational sessions, with the latter mode being able to achieve horizontal positioning accuracy better than 25 cm and 30 cm in a 15-minute long session. Overall, it is noticeable that the most accurate component in PPP solutions is the north component both in single- and multi-GNSS modes.

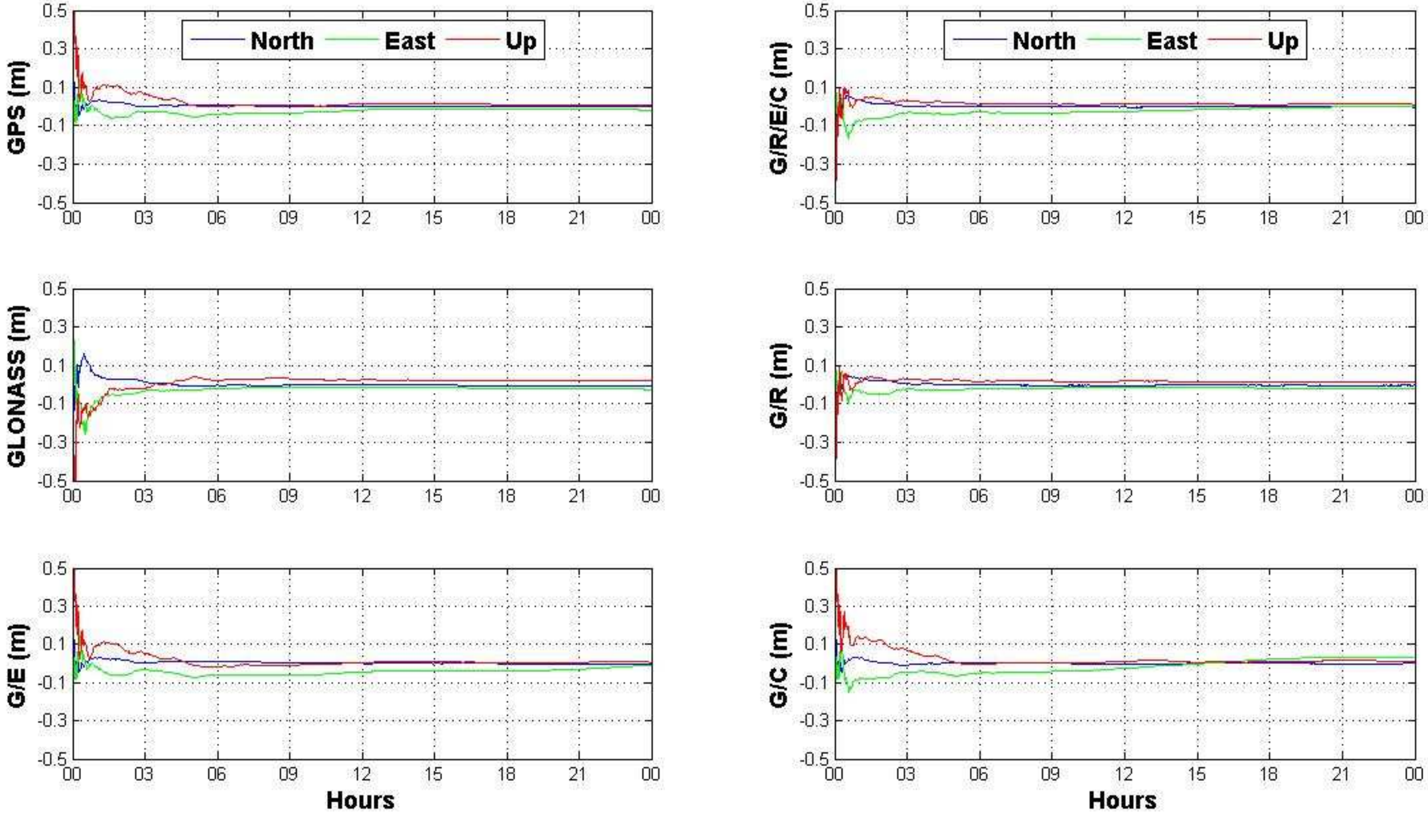

Figure 1: Static PPP performance vs. session duration, at station UNB3. The combination solutions are designated using the notation G (GPS), R (GLONASS), E (Galileo) and C (BeiDou).

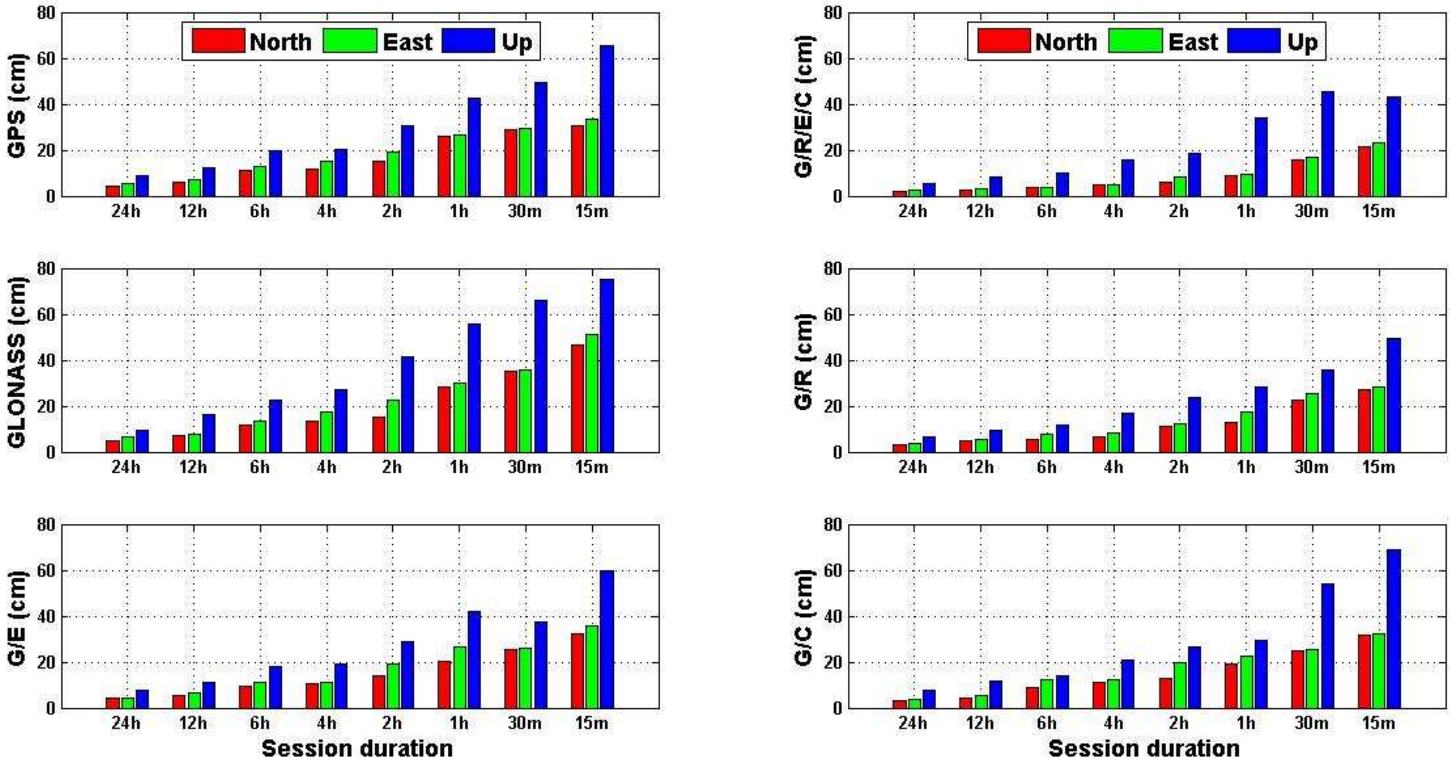

Figure 2: RMSD values of static PPP solutions vs. session duration, at station CUT0. The combination solutions are designated using the notation G (GPS), R (GLONASS), E (Galileo) and C (BeiDou). The north, east and up local components are shown by the red, green and blue color bars, respectively.

4.2 Elevation cut-off angle

The second scenario deals with the dependence of PPP position estimates on the elevation cut-off angles both in single- and multi-GNSS modes.

Figure 3 exhibits the variation of the Root Mean Square (RMS) values of the static PPP solutions, as calculated at station CUT0 for all selected days and for an observation session duration of 24 hours using elevation cut-off angles varying from 10° to 40°. The RMSD values shown indicate that, although the GPS-only PPP solutions generally provide accuracy better than 20 cm in all three components for cut-off angles up to 30°, an improvement of the order of 45% in the PPP positioning accuracy is still possible with the combined use of the four GNSS systems, especially along the North direction.

Clearly, the combination of multiple GNSS systems' data creates a more robust model due to the significant increase of the number of observed multi-GNSS satellites, which even in 40° cut-off angles can reach up to some 15 or more satellites, as compared to only 4-5 GPS satellites being typically observed at such high elevation angles. Generally, it is worth mentioning that, from several such daily session tests performed, while in the case of GPS-only solutions the noted maximum RMSD values in the North and East directions were up to the level of 45 cm, the corresponding maximum RMSD values from the combined GPS/GLONASS and GPS/GLONASS/Galileo/BeiDou solutions were reduced to the level of 15 cm or better.

Most interesting are also the results achieved by the fusion of multiple GNSS data in the pseudo-kinematic case (i.e. treating a stationary receiver as a rover and processing its collected data as kinematic). As shown in Figure 4, the GPS/GLONASS/Galileo/ BeiDou kinematic PPP solutions show greater stability over time compared to the GPS-only and GPS/GLONASS cases. Obviously, the GPS-only mode cannot provide geodetically accurate PPP position estimates as the elevation cut-off angle increases, especially in 30° and 40° where the corresponding position series is characterized by spikes and large deviations from the desired 10 cm threshold; in the same case, the multi-GNSS PPP solutions fall within the 10 cm limit in the North and East directions even in 40° elevation angles.

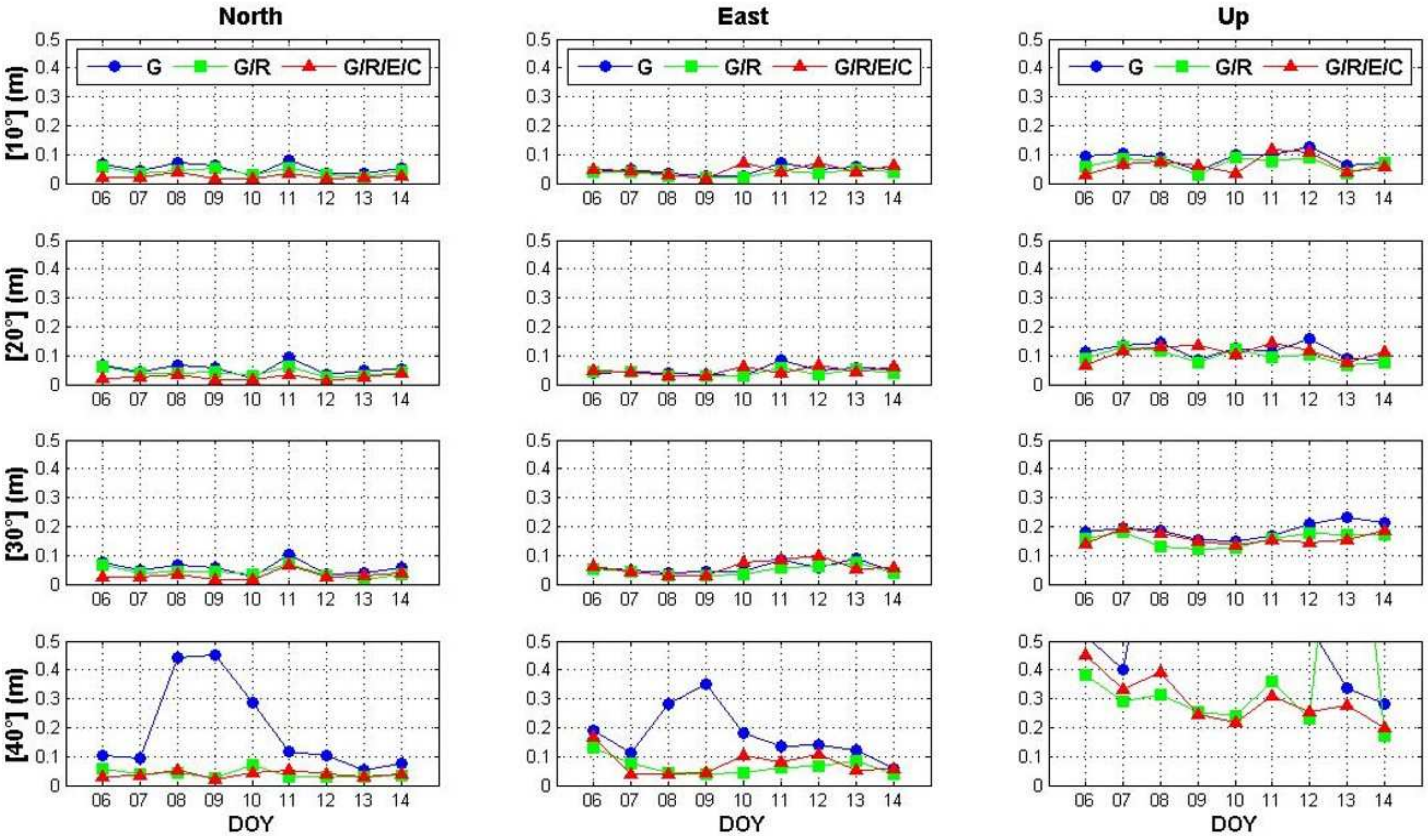

Figure 3: RMSD values (in meters) of static PPP solutions at station CUT0 in a 24-hour long session in single-, dual, and four-system modes under various elevation cut-off angles. The combination solutions are designated using the notation G (GPS), R (GLONASS), E (Galileo) and C (BeiDou).

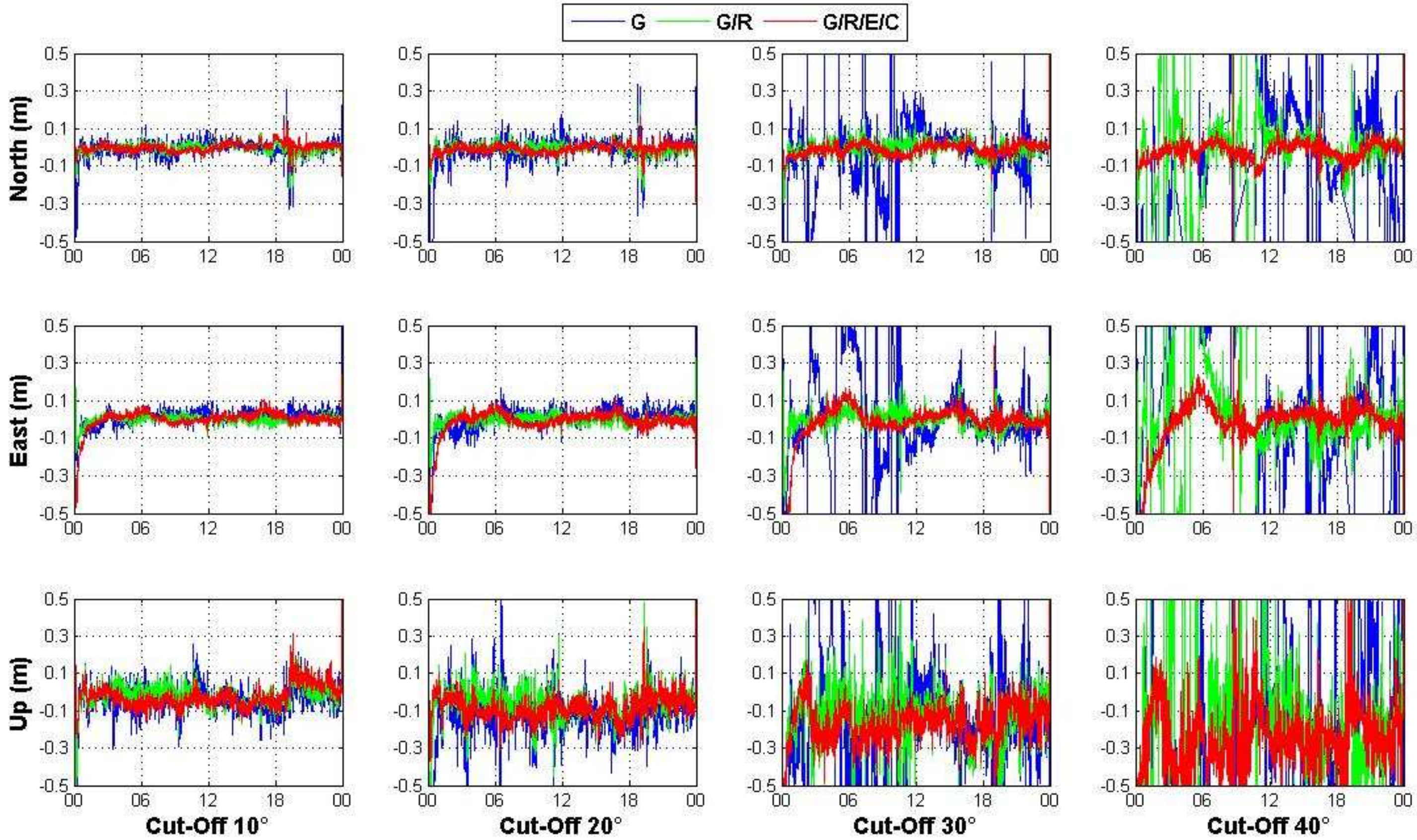

Figure 4: Kinematic PPP performance at station CUT0 in a 24-hour long session in single-, dual, and four-system modes under various elevation cut-off angles. The combination solutions are designated using the notation G (GPS), R (GLONASS), E (Galileo) and C (BeiDou).

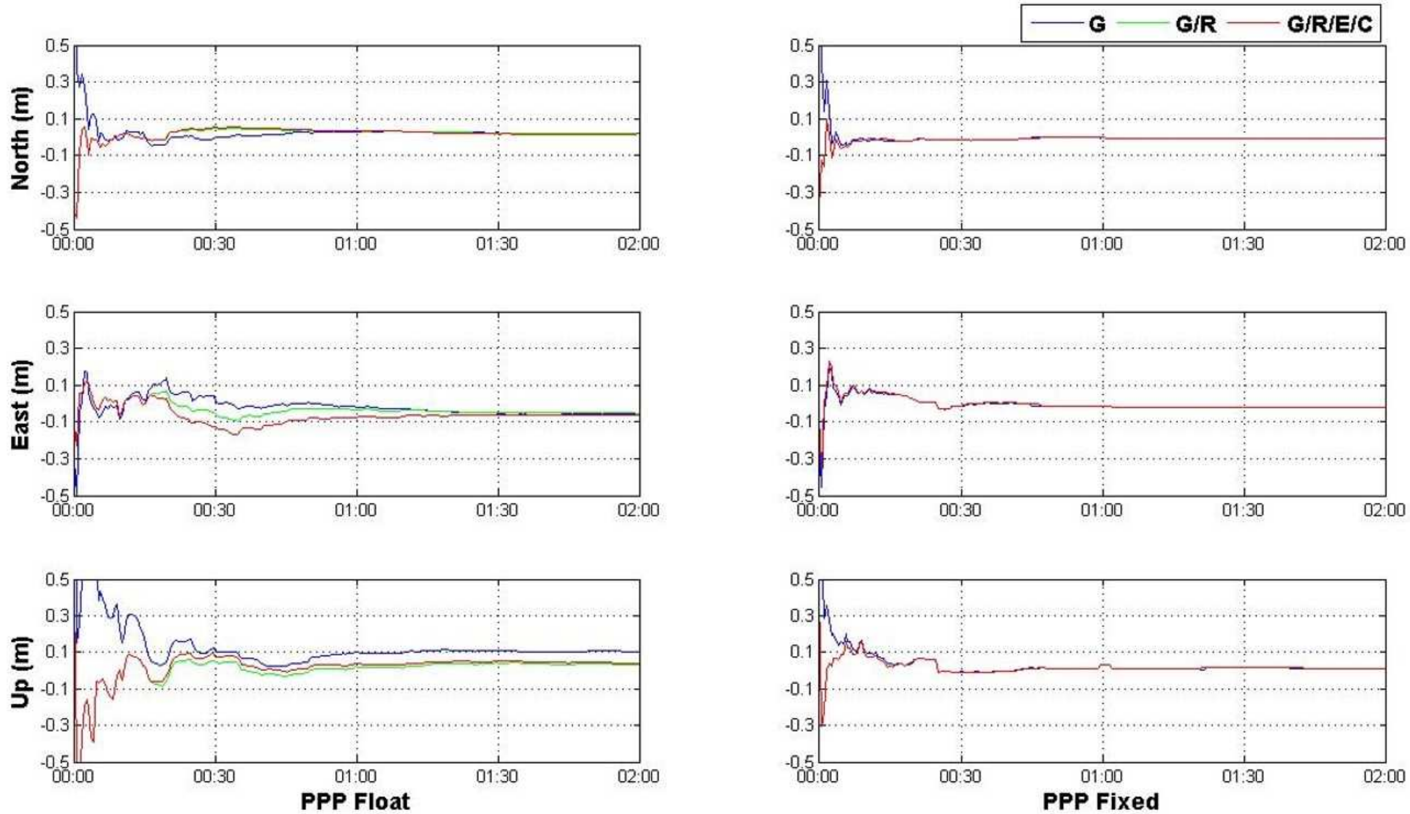

Figure 5: Static PPP performance, at station UNB3, for integer vs. floating ambiguity resolution solutions with data during the first 2 hours on 07/01/2014.

4.3 Integer ambiguity resolution

The performance of the standard PPP processing model is vastly restricted due to the inability to resolve the carrier phase ambiguities to their (inherently) integer values, a fact caused by the presence of the fractional cycle biases (FCB) in the carrier phase observables that cannot usually be separated from the integer ambiguities (Ge et al., 2008). The study of Geng et al. (2009) showed that the integer ambiguity resolution in PPP processing leads to significant increase of the positioning accuracy especially in the East direction, whereas floating ambiguities affect adversely the final solution. Today, such an improvement is practically possible through the clock products provided by CNES since November 2009 (Laurichesse, 2011), which include the wide-lane fractional cycle biases (FCBs).

For most GPS satellites, so-supplied FCBs may exceed half a cycle, which means that their addition to the PPP model is necessary in order to achieve successful integer ambiguity resolution during processing. Figure 5, shows that adding the wide-lane FCBs in the PPP processing shortens significantly the convergence time of GPS-only solutions, since it takes only 5, 5 and 10 minutes for GPS-integer fixed ambiguities solutions to converge to the 10 cm desired threshold while the GPS-floating ambiguities solutions require 7, 20 and 30 minutes in the North, East and Up directions respectively. Overall, in all similar tests performed in our study, it was generally observed that there was a shortening of the convergence time about 65%, 50% and 72% in the directions North, East and Up respectively when externally available GPS FCBs were included in the PPP processing.

5. Conclusions

Combining data from GPS, GLONASS, Galileo and BeiDou systems is becoming increasingly important nowadays, as a means of achieving a geodetically viable position accuracy increase (mostly in the less favorable East direction) and a large reduction of convergence time in PPP solutions compared to GPS-only PPP solutions. GPS-only solutions with data from high elevation cut-off angles, generally lead to position accuracy and convergence time deviating from satisfactory geodetic thresholds. By contrast, respective multi-GNSS PPP solutions not only show improvement, but also lead to geodetic level accuracies even in extreme 40° elevation cut-off angles. Analogous improvement is obtained in multi-GNSS solutions whereby handling the GPS ambiguity resolution problem is done by using externally supplied GPS wide-lane FCBs, even though the respective GLONASS, Galileo and BeiDou carrier phase ambiguities were retained in their floating values, since no relevant information about them is provided, as yet, in the clock products available to date from the IGS analysis centers.

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